AD NUMBER
AD841349
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; OCT 1959. Other requests shall be referred to Army Engineer Waterways Experimentation Station, Vicksburg, MS 39180.**
AUTHORITY
USAEWES ltr 29 Jun 1971

PRELIMINARY STUDY OF STRESSES UNDER OFF-ROAD VEHICLES

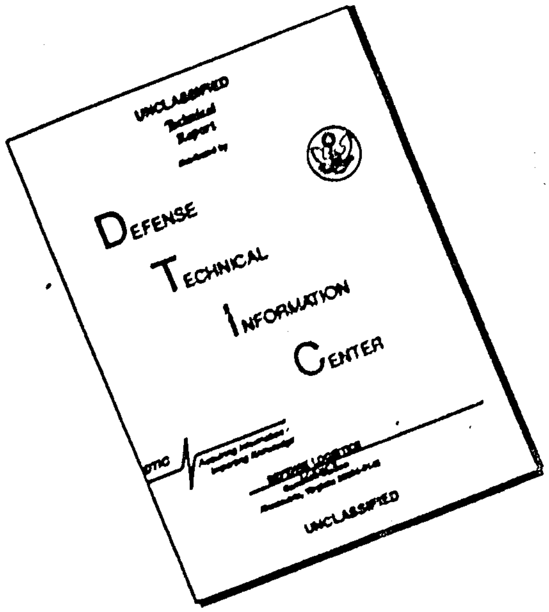
MISCELLANEOUS PAPER NO. 4-362

October 1959

Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

Preface

This paper was presented at the convention of the American Society of Civil Engineers in October 1959. It is based on work sponsored by the Office, Chief of Engineers, and was approved for presentation by that office.

PRELIMINARY STUDY OF STRESSES UNDER OFF-ROAD VEHICLES

John E. Green* and S. J. Knight**

INTRODUCTION

In 1955 the U. S. Army Engineer Waterways Experiment Station was assigned the task of developing quantitative relations between moving vehicles and soil which were to be used in designing military vehicles with improved cross-country capability. This task was a natural extension of studies of the trafficability of soils[1] that had been in progress at the Waterways Experiment Station for several years. The trafficability studies were concerned with determining the ability of soils to permit the passage of existing military vehicles, and were conducted on an empirical basis. From a review of the literature in connection with these studies, it was known that Mr. Richard C. Kerr† had done much toward solving the problem of movement of rubber-tired vehicles on sands, and that Mr. M. G. Bekker†† was considering theories of vehicle movement on all soils, and had performed considerable laboratory research. Thus it appeared that the WES work should be concentrated on soft cohesive soils, and that the studies should begin with the measurement of stresses and strains induced by vehicles in soft soils for comparison with existing theories or perhaps for development of new ones.

In order that a vehicle can cross it, a soil must support the vehicle in a vertical direction, i.e., must keep the vehicle from sinking too deeply, and

* Formerly engineer, Mobility Section, Army Mobility Research Center, Soils Division, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., now engineer, American Construction Company, Cleveland, Ohio.

** Engineer, Chief, Army Mobility Research Center, Soils Division, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

† Geologist, Arabian-American Oil Company (retired). Consulting engineer, New York, N. Y.

†† Chief, Land Locomotion Research Branch, Ordnance Tank-Automotive Command, Detroit Arsenal, Michigan.

must also provide sufficient resistance or friction in a horizontal direction for the vehicle's wheels or tracks to develop a forward thrust, or traction. When rutting of the soil occurs, as often happens under cross-country traffic, resistance to vehicle movement increases because the soil must be compacted or bulldozed aside. When the sinkage and bulldozing effects combined become too great to be overcome by the traction forces, the vehicle becomes immobilized, even though, with the powerful engines of today, the vehicle is usually able to spin its wheels or tracks.

It is apparent that the problem is one of surface soils; therefore, it is not necessarily one involving conventional soil mechanics, which for the most part deals with deeper soils. Surface soils have lower densities and can sustain higher moisture contents than deeper soils. Thus they are much weaker than the soils usually treated in conventional soil mechanics problems. A vehicle traveling on such a soil will sink appreciably, and the soil itself will move appreciably. Strains in the soil near the vehicle will often be of the magnitude of several hundred per cent.

Measurement of the distribution of stresses in soft surface soils under dynamic loads, measurement of relatively great soil movements under such conditions, and development of rational relations between vehicle performance and soil behavior so that designers may have useful tools for improving the cross-country capability of military vehicles are new areas in the field of soil mechanics. While existing theories of soil mechanics will serve as a valuable background, it is probable that new theories to explain and predict the behavior of soft soils under dynamic loads will be developed in accomplishing the assigned task.

In its simplest concept, the problem is similar to other engineering problems in that it concerns the measurement and relation of stresses and strains. The first step toward solving this problem was to obtain

quantitative data on stresses and strains from experiments conducted with vehicles on soft soils. Stresses were measured at predetermined locations and some conclusions concerning the effects of speed and load, etc., were deduced from the experiments.

This paper presents an account of the preliminary research into this new area of soil mechanics. It describes the test procedures used and the results obtained. It is hoped that it will generate interest and encourage contributions from others in this new field of research. The preliminary work is discussed under three headings, Pilot Study, Wheeled Vehicles, and Tracked Vehicles.

PILOT STUDY

A pilot study was conducted to obtain some practical experience in the problem, and to begin development of testing techniques. It consisted of construction of a test lane of heavy clay (CH in the Unified Soil Classification System); application of traffic with a 2-1/2-ton truck with tires inflated to pressures of 15, 30, and 60 psi; measurement of stresses under static and dynamic loads; and determination of soil conditions before and during the tests.

One of the specific aims of the pilot study was to find a device for reliable measurement of stresses under dynamic loads. In previous investigations[2] at the Waterways Experiment Station, a pressure cell designed to indicate stresses in a soil mass had been found to perform with an acceptable degree of accuracy in firm soils and under static loads. So it was necessary to determine whether the cell would also perform satisfactorily in soft soils and under moving loads. In the pilot study, several of these cells were placed at various offsets and depths in the test lane.

The cell, which is 6 in. in diameter and 1 in. thick, consists of a

circular face plate welded at its perimeter to a thicker base plate (fig. 1) and provided with a peripheral slot which forms a flexural joint between the two plates. The thin cavity between the face plate and base plate is filled with mercury, so that pressure on the face plate is averaged and transmitted by the mercury to an internal diaphragm formed by boring the base plate from the rear. The diaphragm section thus provided responds to loading by increased radial and tangential strains. Electrical strain gages affixed to the rear of this diaphragm undergo resistance changes proportional to the applied load as a result of the strains induced in the diaphragm.[3]

The principal conclusion drawn from the pilot study was that the WES pressure cell was satisfactory for further stress studies. This conclusion was based on the finding that stresses measured under the tires of a truck in a fairly soft soil were of about the same degree of accuracy as stresses measured under static loads in firmer soils.[4] However, since the highest degree of accuracy was only about 90 per cent, it was recommended that other types of pressure cells be tested as they became available.

WHEELED VEHICLES

A program of testing was conducted to obtain some knowledge of the distribution of stresses under a wheeled vehicle from pressure cells placed at predetermined locations in the soil. For these tests, the M135, a 6x6, 2-1/2-ton military cargo truck equipped with 11.00-20 tires, was operated on prepared areas of fat clay and lean clay, and a natural area of lean clay. (See fig. 2 for soil data.) Tire pressure and speed of vehicle were varied in the study. Stresses induced by the truck were measured with three sensing devices: the WES earth pressure (EP) cells previously described, WES fluid pressure (FP) cells (see fig. 3), and Consolidated Electrodynamics Corporation (CEC) pressure pickups (see fig. 4). The latter two devices, while

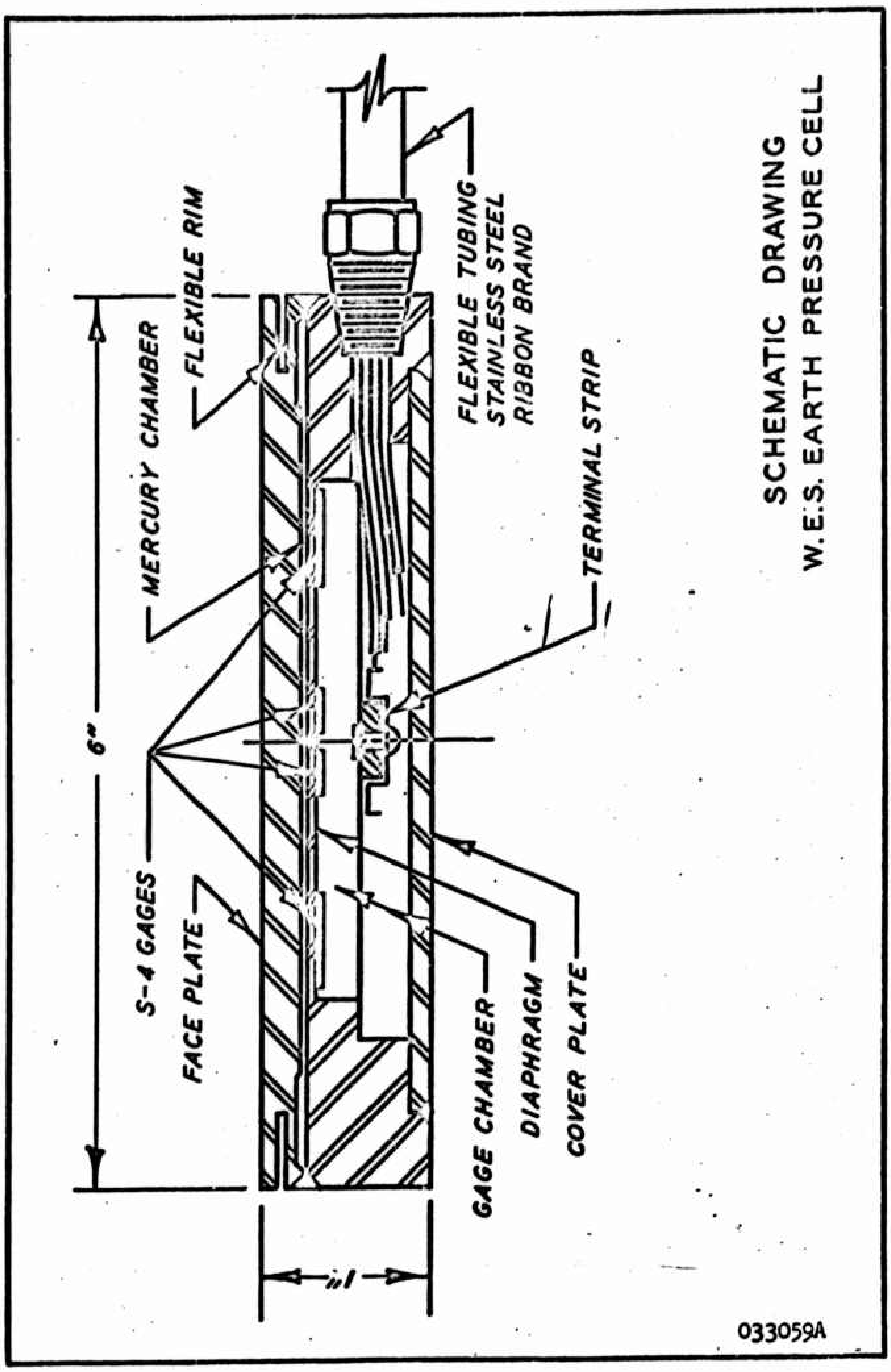
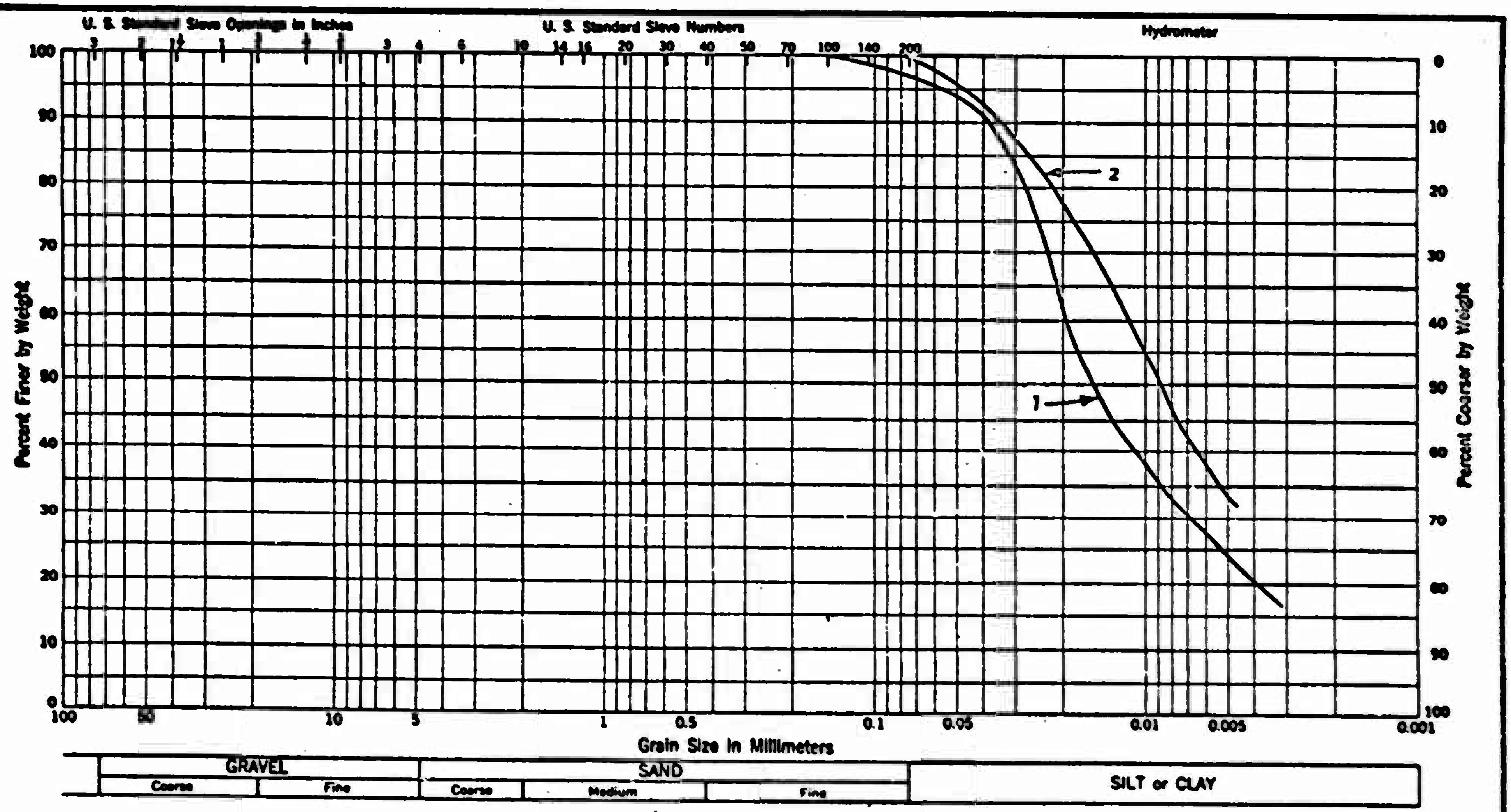

SCHEMATIC DRAWING
W.E.S. EARTH PRESSURE CELL
FLEXIBLE RIM
MERCURY CHAMBER
S-4 GAGES
FACE PLATE
6"
GAGE CHAMBER
DIAPHRAGM
COVER PLATE
FLEXIBLE TUBING
STAINLESS STEEL
RIBBON BRAND
TERMINAL STRIP
033059A

FIGURE 1

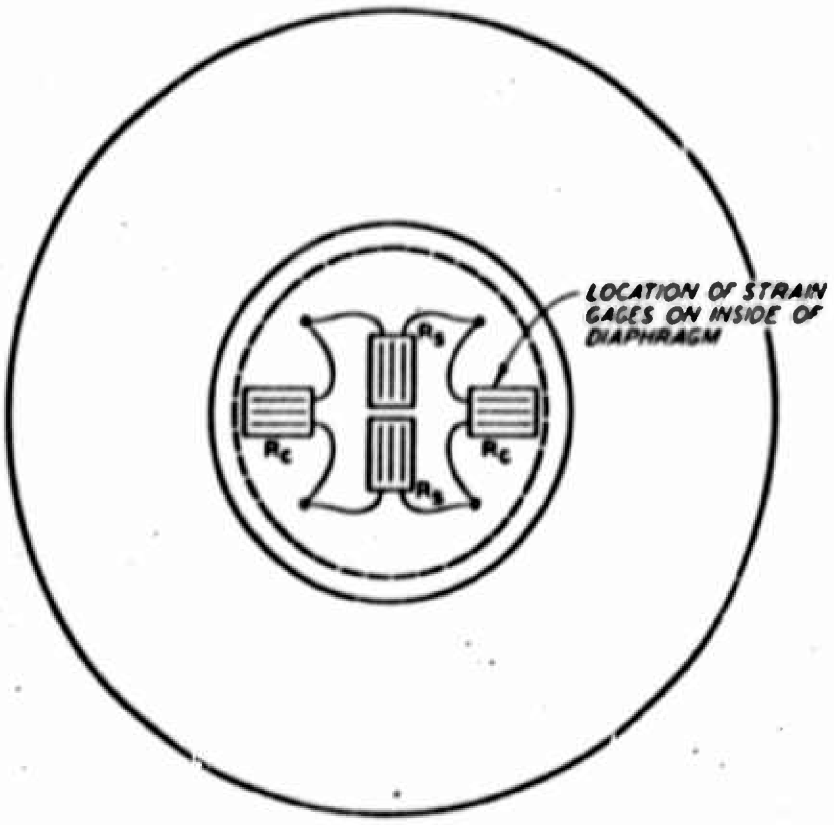


Number	Depth	Natural Moisture	L. L.	P. L.	P. I.	Classification
1			38	20	18	LEAN CLAY (CL)
2			60	21	39	HEAVY CLAY (CH)

SOIL CLASSIFICATION DATA

011458-B

FIGURE 2

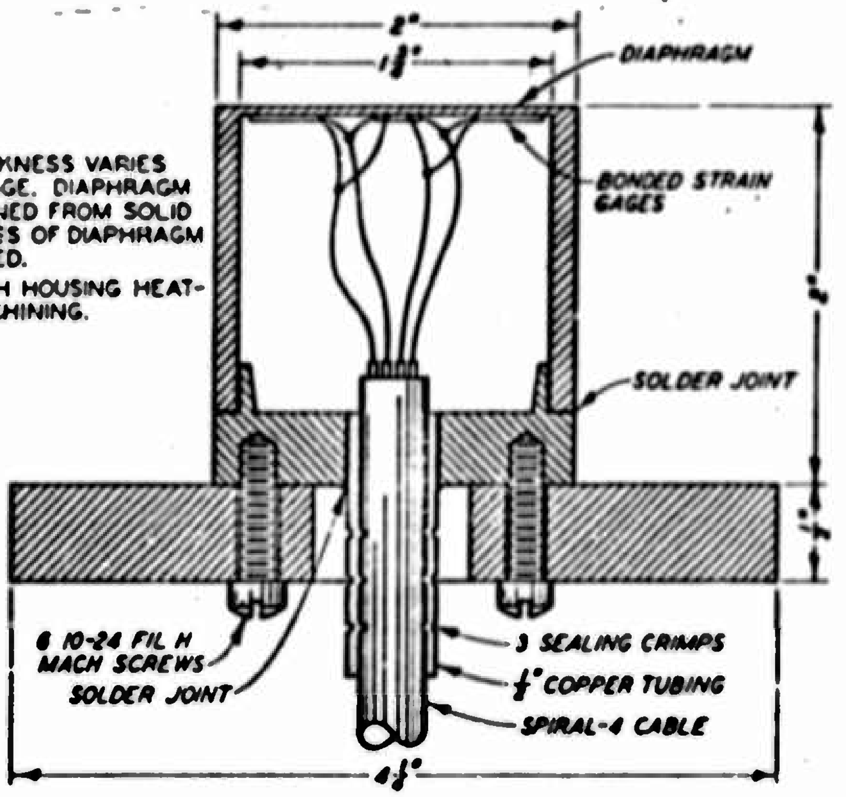


TOP VIEW

NOTE:

DIAPHRAGM THICKNESS VARIES WITH PRESSURE RANGE. DIAPHRAGM AND HOUSING MACHINED FROM SOLID STOCK AND THICKNESS OF DIAPHRAGM CLOSELY CONTROLLED.

DIAPHRAGM WITH HOUSING HEAT-TREATED AFTER MACHINING.

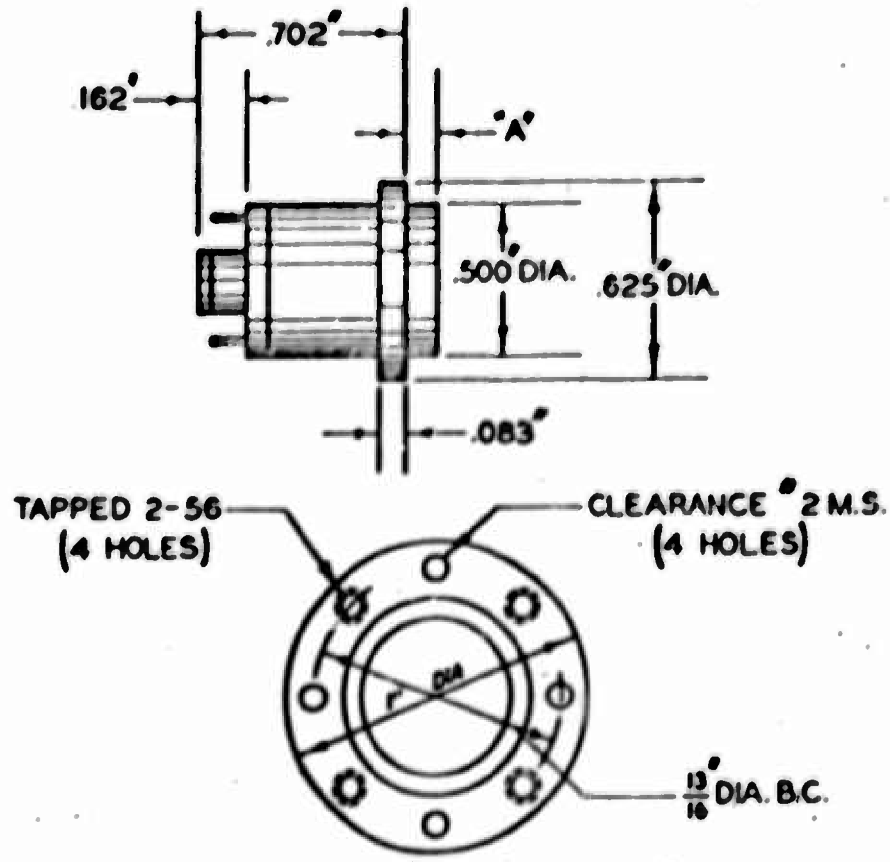


SECTIONAL ELEVATION

WES FLUID PRESSURE CELL

120498 J

FIGURE 3



MOUNTING FLANGE

PRESSURE RANGE-PSI	"A" DIMENSION
5	.094
10	.095
15	.095
25	.097
50	.098
150	.103

CEC TYPE 4-312 PRESSURE PICKUP

120434E

FIGURE 4

normally used in fluids, were included in the investigation to determine whether they could be reliably used in very wet, soft soils.

The first test area consisted of 4 ft of prepared fat clay (CH under the Unified Soil Classification System, locally termed "buckshot") placed in 6-in. lifts. Water was added to each lift to attain the desired moisture content, and each lift was compacted a specified amount. The second area was natural ground (lean clay, CL) from which the vegetation had been removed. The third area consisted of 2 ft of prepared lean clay (CL) that was placed at the desired moisture content in 3-in. lifts. Pressure cells were installed by digging a hole at the desired location and to the desired depth, placing the cell, and backfilling the hole. Backfill material was placed and compacted by hand, with efforts being made to attain a soil strength equal to that of the adjacent soil.

In the tests where rutting was anticipated, the truck was operated so that one line of truck wheels traveled in the cell area and the other traveled in a guide path consisting of two rows of 2- by 4-in. planks placed on edge, spaced the width of the tire apart, and tied down with rods driven into the soil. In the tests where no rutting was expected, a guide constructed of two steel angle sections was used. Fig. 5 shows the truck passing over the test area with the left wheels over the cell area and the right wheels in the channel formed by the two steel sections.

The first series of tests in this investigation was conducted to determine the effect of soil strength or consistency on the stresses induced in the soil by the same load. The pressure cells were similarly placed in both firm and soft soil areas and an identical pattern of traffic was applied to each area; however, deep rutting and excessive cell movement in the soft soil prevented clear-cut comparisons, and results were inconclusive.

Fig. 6 pictures a representative pressure cell response as received on a

FIGURE 5

direct-recording oscillograph. The pattern and magnitude of the stress induced by each of the wheels on one side of the M135 are shown; they indicate that the highest peak stress occurred under the rear tandem, while the lowest peak stress occurred under the front tandem wheel. This order of magnitude of peak stress agrees with the static axle loads of 5900, 5600, and 6100 lb for the front, front tandem, and rear tandem axles, respectively. It must be admitted, however, that all the recorded data were not as clear-cut as the data shown in fig. 6. Inconsistent data have been attributed to any one or a combination of several factors, such as variable path of the vehicle due to guide channel movement in the soft soil, cell movement during the response period, stress concentration or dispersion due to variable soil conditions above and adjacent to the cell, or improper cell seating. Measures will be taken to eliminate or diminish the effects of these factors in future investigations.

The effect of tire inflation pressure on induced stresses was also investigated in a fairly soft fat clay. Two pressures, 15 and 60 psi, were used in the tests. On the basis of limited comparisons, it was tentatively concluded that tire inflation pressure had no significant effect on the maximum stresses induced by the M135 truck, at least below a depth of about 5 in., in a soft clay.

Pressure cells, embedded in the firm, lean clay area so that the faces of the cells were flush with the surface of the soil, were used to measure contact pressures of the truck moving across the soil. Tire pressure was 15 psi. Some of the pressures recorded in these tests showed complex patterns of pressure distribution under the tire area, with point pressures varying from 10 to 60 psi. The general validity of the patterns was established by a later, more closely controlled study of tire contact pressures. Pressure cell response (fig. 7) showed that the pressure decreased as the center of the tire approached and passed over the center of the cell; in other words, the leading

and trailing edges of the tire induced higher pressures than the interior portion. The tests also revealed that speeds ranging between 2 and 8 fps had no discernible effect on the recorded maximum stresses.

While this preliminary investigation of the distribution of stresses induced in soft soils by a moving truck did not permit confident conclusions of a general nature because of the usual pitfalls associated with the investigation of unknown phenomena, it was considered worthwhile in that it provided experience in conducting research of this nature. Such items as recognizing (a) where emphasis should be placed to attain optimum effectiveness in future tests, (b) the degree of control in soil preparation, cell installation, and traffic application necessary for obtaining reliable data, and (c) the quantity of data necessary to meet specific objectives are important from the standpoint of planning and conducting future research of this nature.

TRACKED VEHICLES

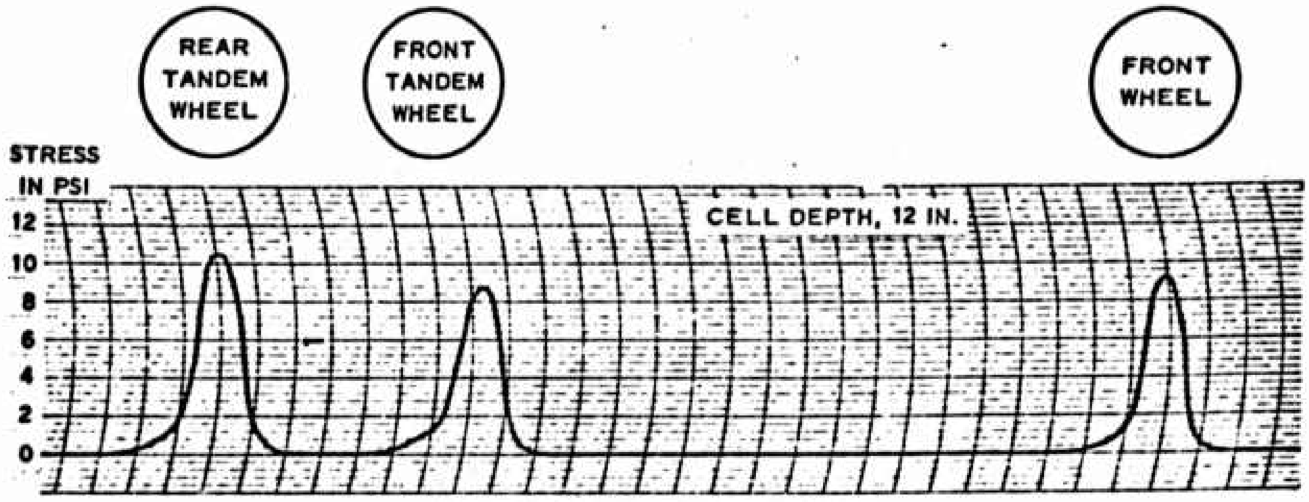
The tracked vehicle program was conducted to obtain general information on the distribution of stresses and to compare stresses under three vehicles, an M29C (Weasel), a D-4 engineer tractor, and a D-7 engineer tractor. Two prepared areas of fat clay (buckshot)--one soft, the other fairly soft--were constructed as for the tests with wheeled vehicles, with the EP, FP, and CEC cells installed at predetermined depths and offsets immediately after construction. Speed, load, and direction of the moving vehicle were varied during the testing.

The first test was conducted with the M29C trafficking the fairly soft area under five different conditions: (a) slow speed (approximately 2 fps), no added load; (b) fast speed (approximately 9 fps), no added load; (c) slow and fast speeds, 500-lb added load; (d) slow and fast speeds, 1000-lb added load; and (e) backing, 1000-lb added load. Early in the test it was noted

that the recorded stress patterns showed that higher stresses occurred beneath the individual bogies than under other areas of the track (fig. 8). Fig. 8 also shows that the second and seventh bogies (as numbered from front to rear) induced considerably higher stresses (at the same depth in the soil) than any of the others and that the first and eighth bogies induced the lowest stresses. The unusual stress pattern was attributed to a combination of the flexibility of the track and the track tension: the former allowed the bogies to transmit most of their load without distributing it along the track, while the latter, in conjunction with the suspension design, caused a portion of the load on the end bogies to be transferred to their adjacent bogies.

The suspension system of the M29C consists of four transverse springs fastened to the bottom of the hull and a bogie spring suspension yoke fastened to both ends of each transverse spring. The yoke supports a bogie support arm, on each end of which the two bogies are mounted; in other words, it is a spring suspension system with bogies mounted in pairs. With this system, if one of the bogies cannot carry all its load, the portion that it cannot support is transferred to the other bogie. The track tension causes a lifting force on the two end bogies. This action, in turn, causes some of the load carried by the end bogies to be transferred to their adjacent bogies. The net result is indicated by the stress pattern in fig. 8.

Qualitative analysis of the maximum stresses induced by the bogies has indicated some of the effects of the various operating conditions. It was found that the major portion of load added to the M29C was transmitted to the bogies inducing the lower stresses, so that while total stresses were increased, the soil was not subjected to significantly higher maximum stresses. From these data it was concluded that loads up to at least 1000 lb (the limit of this study) can be carried by the M29C without seriously impairing the capability of the vehicle to cross soft soil.



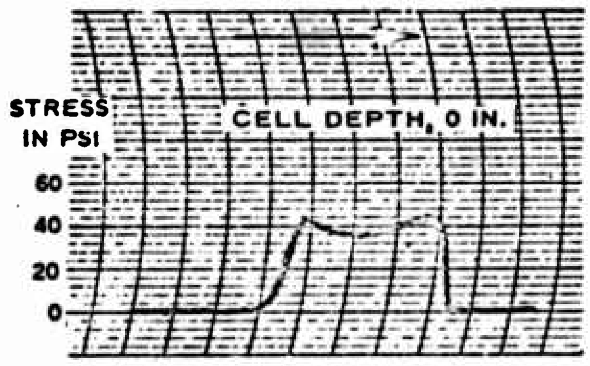
STRESSES IN FINE-GRAINED SOIL

M135 2-1/2-TON TRUCK

15-PSI TIRE INFLATION PRESSURE

032059C 2933-LB WHEEL LOAD

FIGURE 6



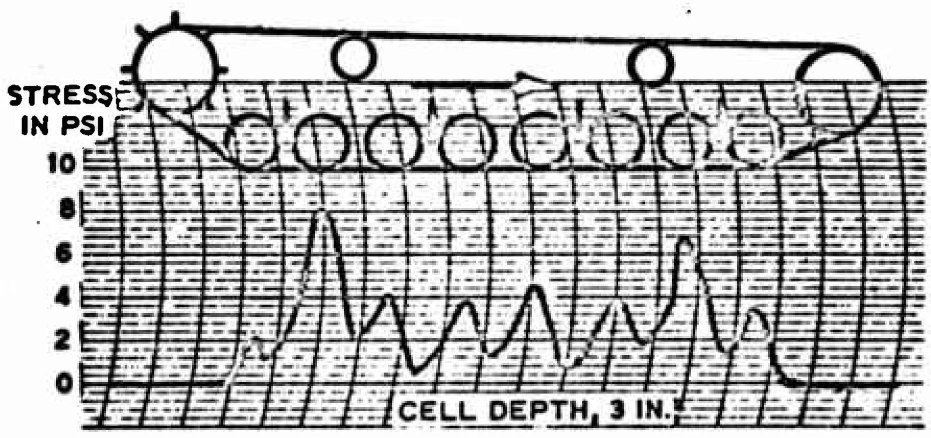
STRESSES IN FINE-GRAINED SOIL

M135 2-1/2-TON TRUCK

15-PSI TIRE INFLATION PRESSURE

032059B 2933-LB WHEEL LOAD

FIGURE 7



STRESSES IN FINE-GRAINED SOIL

M29C WEASEL

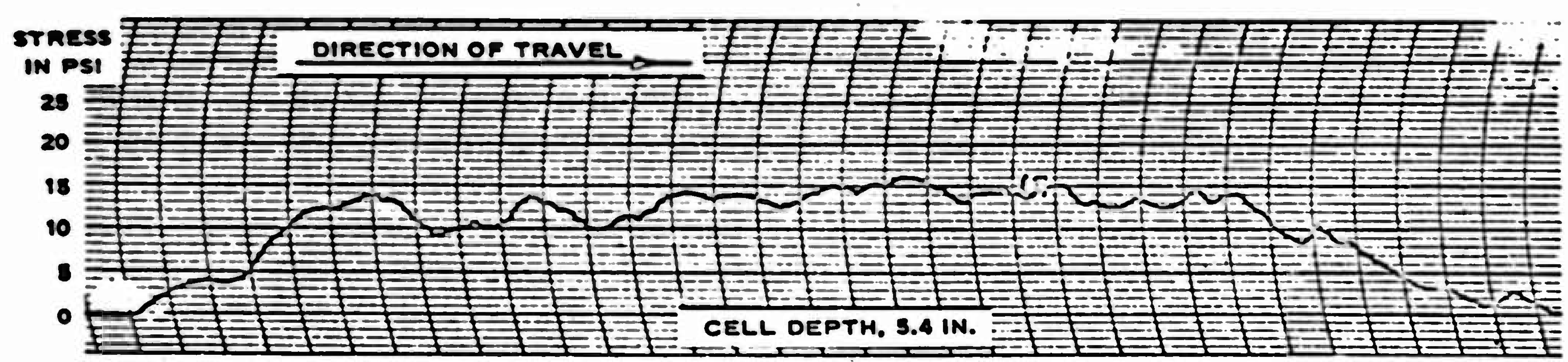
032059E 1.8-PSI CONTACT PRESSURE

FIGURE 8

It has been mentioned that the second and seventh bogies induced higher stresses than did the other bogies when the M29C was moving forward. As fig. 8 shows, the seventh bogie induced a higher stress than the second, but when the vehicle traveled in reverse, the action was changed, i.e., the second bogie induced a higher stress than the seventh with both still transmitting higher stresses than the other bogies. Thus, regardless of the direction of travel, the second bogie to pass a given point induced the second highest stress while the seventh bogie induced the highest stress. This indicates that the effective load distribution is not static but is apparently dependent upon the direction of travel.

The attempt to determine the effect of speed on stresses induced by the M29C was only partially successful. The relatively fast passes of the vehicle indicated that (a) somewhat higher stresses were induced than occurred at slower speeds, and (b) the increase in stress due to speed decreased with depth of soil. These findings were tempered somewhat by the data obtained when the loaded vehicle (both 500 and 1000 lb) was operated at faster speeds for two passes of each load. These latter data did not indicate a general trend of higher stresses for faster motion, so that it was difficult to form definite conclusions on the basis of the contradictory data. It can only be stated that there seems to be a trend of higher stresses at faster speeds, but verifying tests must be conducted.

The pressure cell responses received as the D-4 and D-7 engineer tractors moved over the test areas were quite different from those of the M29C tests. In the latter tests, the well-sprung bogies were definitely responsible for the transmission of peak stresses to the soil but, while the stress patterns beneath the D-4 and D-7 tractors showed peaks, they were less pronounced and there was no correlation of the peak stresses with track roller positions. (See fig. 9 for typical stress pattern.) The bogies of the D-4



STRESSES IN FINE-GRAINED SOIL
D4 TRACTOR
8.3-PSI CONTACT PRESSURE

FIGURE 9

and D-7 tractors are unsprung and attached to a rigid frame, and the track itself is very rigid. The patterns obtained in this test were similar to those obtained with a comparable track assembly tested by the National Tillage Machinery Laboratory at Auburn, Alabama.[5] The NTML concluded that the major portion of the stress pattern vibration was due to the rise and fall of the polygon drive sprocket on the chain and the change in acceleration of the track caused by the drive sprocket. This explanation was tentatively accepted by WES.

The soft soil on which these tests were conducted allowed cell movement under the application of traffic. The cell movement indicated the direction in which the soil was moved. From the cell movement, it was determined that the soil moved laterally away from both sides of the longitudinal center line of the track and, also, in a direction opposite to that of the traffic movement. Under the heavier loads of the D-7 tractor, distinct upward movements of the soil occurred near or beyond the edge of the track.

Only general information in regard to the stress picture beneath the moving engineer tractors has been obtainable from the data taken during these tests. In many of the tests the stresses measured during the first few passes were quite different from those measured later in the test. In the majority of cases, this was attributed to the nature of the cell installation process described earlier in the paper. The fact that the soil had been backfilled around and above the cells and compacted by hand, allowed different installations to have different degrees of compaction which in turn could have caused concentration or dispersion of stresses during the first few passes. Stress data obtained after the first few passes appeared to be somewhat more consistent, probably because the soil around the cells had been compacted to approximately the same degree and the cells were much better seated in the soil. The adequacy of the data for a rigorous analysis was also influenced by the

soil and cell movement which caused variable conditions for different passes, particularly in regard to the distance between the load and the cell and the tilt of the cell. Despite the uncertain nature of the data, significant qualitative information on stresses induced by the engineer tractors was obtained from the test programs, and will be used to guide future investigations.

Some general trends indicated by this latter portion of the investigation are: the highest stresses were measured beneath the lateral center of the track with the stress decreasing with increasing distance away from the center; directly beneath the center of the track and at an approximate depth of 9 in., the horizontal stresses were about 70 per cent of the vertical stresses; and finally, at offsets of 6 to 12 in. from the track center and at an approximate depth of 9 in., the horizontal and vertical stresses were of the same order of magnitude at the same point.

SUMMATION

This study, which was very limited in scope, is the first step taken by the Waterways Experiment Station toward solving the problems of developing vehicle-soil relations which may be of value to the designer of vehicles from an off-road standpoint. The greatest value of this investigation lies in providing information regarding test techniques for use in more comprehensive research programs in the future. Some information, mainly of a qualitative nature, was obtained which shows decided trends of pressure distribution in soft soils beneath the tires or tracks of the vehicles tested.

REFERENCES

1. U. S. Army Engineer Waterways Experiment Station, CE, Trafficability of Soils; A Summary of Trafficability Studies Through 1955. Technical

Memorandum No. 3-240, 14th Supplement, Vicksburg, Mississippi, December 1956.

2. U. S. Army Engineer Waterways Experiment Station, CE, Investigations of Pressures and Deflections for Flexible Pavement; Homogeneous Sand Test Section. Technical Memorandum No. 3-323, Report No. 4, Vicksburg, Mississippi, December 1954.

3. ________, Pressure Cells for Field Use. Bulletin No. 40, Vicksburg, Mississippi, January 1955.

4. ________, Stresses Under Moving Vehicles; A Pilot Study of Waterways Experiment Station Earth Pressure Cell Action in Comparatively Soft Soil. Miscellaneous Paper No. 4-230, Report No. 1, Vicksburg, Mississippi, July 1957.

5. Cooper, A. W., and Reaves, C. A., Stress Distribution in the Soil Under Tractor Loads. Presented at 5th International Congress of Agricultural Engineering, Belgium, September 29-October 4, 1958.